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IMPROVEMENT OF THE RESPONSE OF A SILICON DETECTOR BY THE ADDITION OF LAYERS OF COPPER OR TIN

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ABSTRACT

The response enhancement of a silicon radiation detector by the addition of thin layers of copper or tin has been investigated experimentally at 145 keV and by computer methods over a range of photon energies. It has been demonstrated that this technique can be used, along with the appropriate choices of photon filtration and cut-off energies, to improve the energy response of a silicon detector of thickness 200 to 300 μm.

RÉSUMÉ

Ce rapport présente les résultats de l'étude sur l'amélioration de la réponse d'un détecteur de radiation au silicium, par l'ajout de minces couches de cuivre ou d'étain; étude réalisée théoriquement par ordinateur sur une gamme d'énergie de photon et expérimentalement à 145 keV. Il y est démontré que ce processus peut être utilisé pour améliorer la réponse d'un détecteur au silicium d'un épaisseur de 200 à 300 μm, à condition d'utiliser un choix approprié d'énergies de coupure et des filtre de photon.

INTRODUCTION

Silicon radiation detectors are generally operated in the pulse-counting mode using pulse-height discrimination in order to eliminate noise pulses due to leakage currents. This, of course, also rejects any radiation-induced pulses which fall below the discrimination level. For the Compton process, where the scattered photon carries off a fraction of the primary photon energy and only a portion of the initial photon energy is absorbed in the detector, the response of the detector will depend on the degree to which the energy E_γ of the incident photon exceeds the cut-off energy E_c corresponding to the discriminator level. Thus, for small detectors where re-absorption of the scattered photon can be ignored, the detection efficiency is significant only if $E_\gamma - E'_\gamma = E_e$ exceeds E_c, E'_γ being the minimum scattered photon energy; in this case E_e is the maximum energy absorbed in the detector and is referred to as the Compton edge. The effective cut-off energy for pulses due to the Compton process occurs for photons of energy $E_\gamma = E_{cc}$ for which $E_e = E_c$. For photon energies greater than E_{cc} the response increases sharply at first as the number of pulses with $E_e > E_c$ increases as E_γ increases. For E_γ less than E_{cc} but greater than E_c almost all the response is due to the photoelectric effect. Since the photoelectric cross-section decreases sharply as E_γ increases, a minimum in the detector response is generally observed for $E_\gamma = E_{cc}$. This is the case for silicon detectors at practical values of E_c, as discussed in earlier reports (McGowan (1,2,3)). For example, with $E_c = 60$ keV a sharp minimum in the response is predicted for a photon energy at 157 keV as shown by the solid curve in Fig. 1. This is the energy at which $E_\gamma = E_{cc}$ when $E_c = 60$ keV, the corresponding minimum scattered photon energy being 97 keV. The theoretical minimum response at this point is about one-third the average response at higher energies.

Some calculations of response enhancement at energies near E_{cc} by the addition of copper layers adjacent to the detector were included in Ref (3). These calculations have been extended here to include thin layers of tin. Experimental measurements have been conducted using a ^{141}Ce source (E_γ = 145 keV) with layers of copper or tin adjacent to the surface of a silicon particle detector to test the practical aspects of this means of response enhancement.

MODIFICATION OF RESPONSE AT E_{cc}

The sharp minimum of response, predicted at E_{cc} by computer calculations, for silicon detectors is modified, in practice, by several factors including: (1) electronic noise, most of which originates in the detector; (2) the use of non-monoenergetic photon sources; (3) photon scattering by materials in the vicinity of the source or the detector; and (4) electron scattering from materials adjacent to the detector.

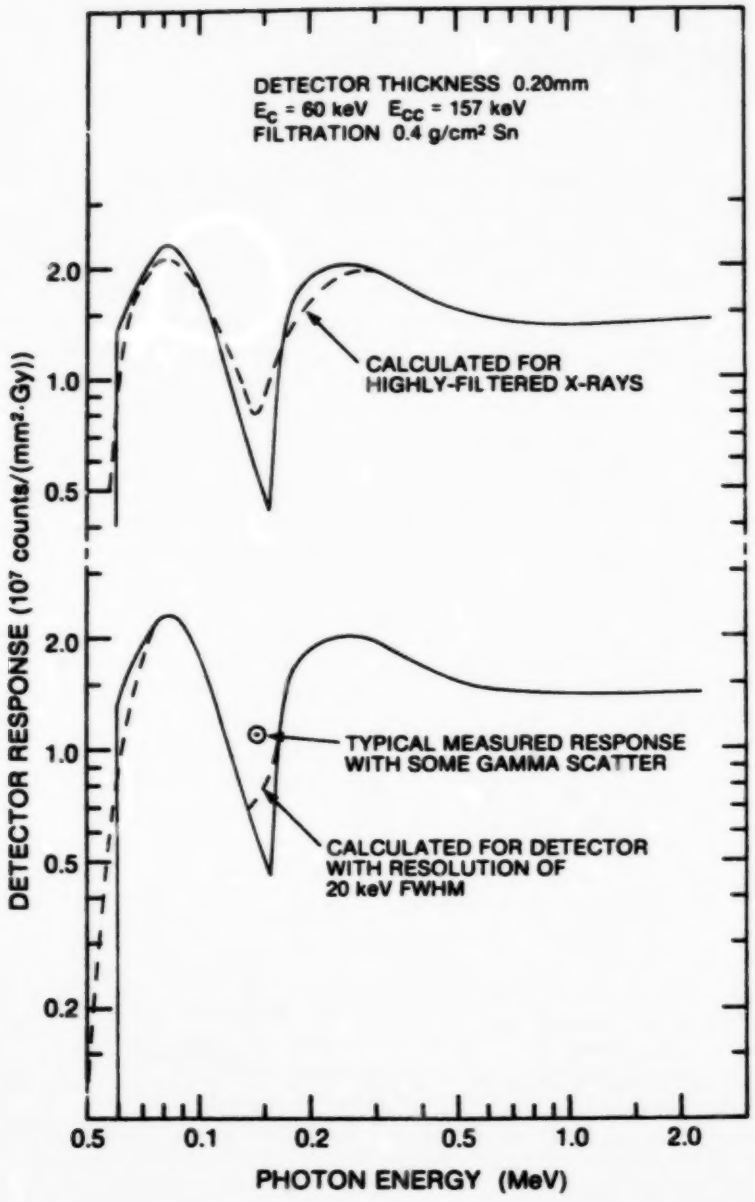

Figure 1. Solid curve shows the calculated response, taken from Ref. (3), of a 0.2-mm silicon detector with cut-off energy 60 keV and 0.4 g/cm² tin filtration. The upper dashed curve shows the modified response which might be obtained using x-rays instead of monoenergetic photons. The lower dashed curve indicates modification of response due to imperfect resolution. The single point at 145 keV is typical of the measured response where there is considerable scattered radiation from the 145-keV source.

The first two of the above factors were examined briefly by computational means. Detector noise causes monoenergetic pulses to be spread in a Gaussian distribution which can be characterized by the full width at half maximum (FWHM). The effect of this on the response was calculated at 150 and 175 keV starting with the calculated spectra of Ref. (3) and spreading the energy bins according to the error function with a FWHM of 20 kev. The sharp minimum at E_{cc} in Fig. 1 (at 157 keV) is modified as shown by the dashed curve in the lower part of Fig. 1. Also shown, is the estimated modifications to the response at energies near E_c (60 keV). Reduction in the response above E_c is accompanied by inclusion of some response for E_γ below E_c since the noise level can increase or decrease the amplitude of the radiation-induced pulses.

While poor resolution is seen to produce some improvement in energy response, it is more important to maintain reasonably good resolution to prevent noise pulses from exceeding E_c, allowances having to be made for the increase in noise level with increase in operating temperature.

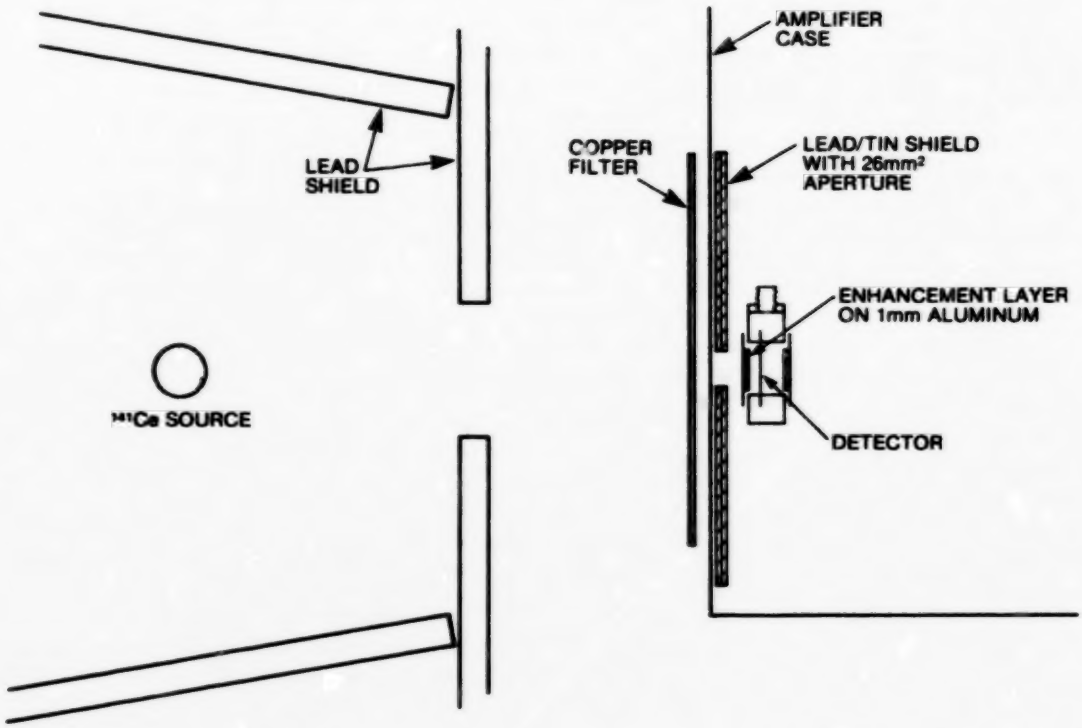

Figure 2. Experimental arrangement used to minimize the fraction of scattered photons reaching the detector and to eliminate edge effects of the detector's sensitive area.

When response measurements are made with sources which are not monoenergetic, the measured values can vary appreciably from those of the mean source energies if the response is highly energy dependent. Measured responses using x-rays can be expected to be higher than predicted for mean energies near the response minimum in Fig. 1. Estimates of this effect were made using the spectral distributions of highly-filtered x-rays as measured by Jones and Benyon (4). The modified response is shown by the dashed curve in the upper part of Fig. 1 where the minimum response is seen to be roughly twice that calculated for a monoenergetic source. In fact, experimental measurements using x-ray sources tend to show even less of a minimum than indicated here (see Jones (5) and also Ref. (2)).

The effect of photon scattering on the detector response was investigated briefly by measurements with ^{141}Ce gammas. To approach conditions for which the calculations of Ref. (3) were performed, a silicon particle detector with a transmission-type mounting was used in the experimental arrangement shown in Fig. 2. The aluminum front and back layers correspond to the wall material used for the calculations. The copper filter (1.0 mm) was used to remove the 37-keV x-rays from the ^{141}Ce source. This also reduces the 145 keV gamma intensity by about 11%, which is about the same attenuation as for 0.2 mm of tin, and makes about the same contribution to the scattered gamma intensity as 3 mm of silicon (or aluminum). Other contributions to scattering from the collimator edges, from the lead behind the source and from distant materials behind the detector should be small.

The experimental spectrum obtained with the arrangement of Fig. 2 is shown by the solid curve in Fig. 3. The ^{141}Ce peak is seen at 145 keV with a resolution of 11 keV (FWHM). The steepness of the Compton edge at 53 keV is also degraded because of detector noise so that some of the Compton pulses are observed above this energy.

The 26-mm^2 aperture permitted only the central portion of the 61-mm^2 detector to be irradiated. Increasing the aperture to 70 mm^2 showed about 20% increase in the relative number of counts below the peak, presumably because of scattering at the edge of the detector's sensitive volume. Increasing the aperture area to 285 mm^2 permitted the detector mounting including a Plexiglas holder to be irradiated. The spectrum obtained under these conditions is shown by the short-dashed curve of Fig. 3 which is normalized to the solid curve at the 145-keV peak. A considerable increase in the relative number of pulses between 60 and 130 keV can be seen. Most of this can be attributed to scattered photons from the detector mount.

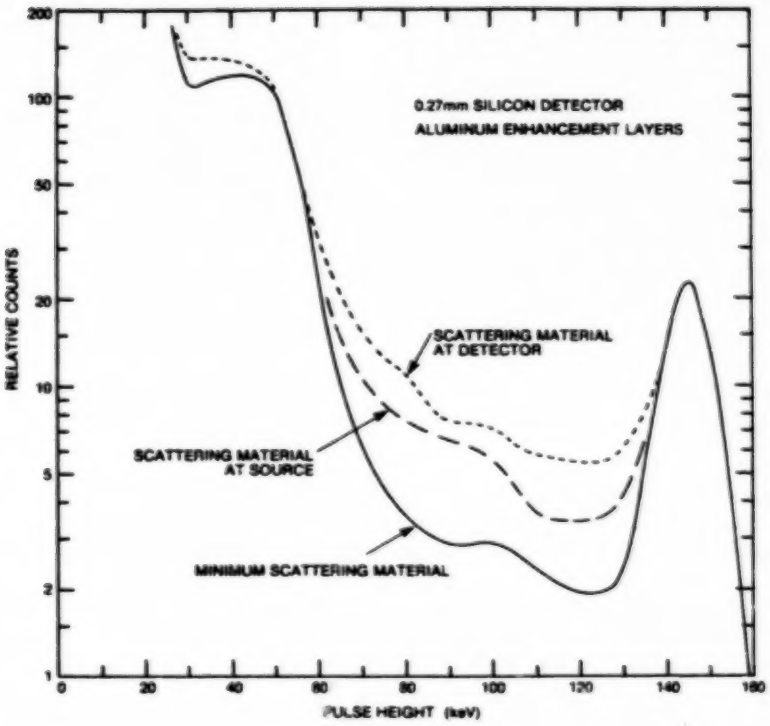

Figure 3. Measured pulse-height spectra. The solid curve was obtained with the setup in Figure 2. For the long dashed curve the lead shield around the source was removed and about two inches of wood was added just behind and at the sides of the source. For the short-dashed curve the aperture in the lead/tin shield was opened to expose the entire detector case and supporting plastic holder.

The long-dashed curve in Fig. 3 was obtained with the 26-mm^2 aperture in place but with the rectangular lead collimator removed and with two inches of wood surrounding the source and acting as a scattering medium. The relative values of the measured responses listed in Table I indicate the relative contributions of scattered radiation to the detector response at various cut-off energies for the scattering bodies used at the detector or source. The theoretical response minimum occurs at photon energy 145 keV ($E_\gamma = E_{cc} = 145$ keV) with $E_c = 53$ keV. The largest relative increases in response are seen to occur near this value of E_{cc} as the result of the production of scattered photons with lower energies and, therefore, higher photoelectric absorption cross sections.

TABLE I

Response of 0.27-mm Silicon Detector to 145-keV Photons in Units of 10^7 counts/(mm^2 gray(tissue))

	Measured Response			Calculated Response
E_c (keV)	No Scatter	Scatter at Detector	Scatter at Source	
40	4.2	5.4	4.5	4.54
50	2.2	3.1	4.5	1.87
60	1.10	1.73	1.43	0.93
75	0.80	1.25	1.00	0.84
100	0.66	0.87	0.73	0.76
125	0.56	0.65	0.57	0.70

The measured responses are based on dose-rate measurements taken with an ion chamber behind the copper filter with the source in a lead castle. These will include a small scattering contribution from the lead which is not present for the "no scatter" measurements, so that the "no scatter" responses are slightly low. The responses with the scatterer will be somewhat high because of the additional scattered-photon dose which is not included in the calculations.

The detector used for these measurements was 0.27 mm in thickness and under the operating bias applied (80 V) was found to be essentially fully depleted. The thin gold front layer (40 $\mu g/cm^2$) should have little effect at 145 keV. The calculated responses in Table I were obtained with the CYLTRAN computer code (Halbleib and Vandervender (6)), used in Ref. (3), with the same basic geometry used for the measurements with minimum scatter. The calculations were done with silicon in place of the 1-mm aluminum layers used in the measurements as shown in Fig. 2. The difference between the results using either of these two materials should be negligible since the atomic numbers of aluminum and silicon are 13 and 14, respectively.

The measured (no scatter) responses at values of E_c of 100 and 125 keV are seen in Table I to be about 15% below the calculated values. This may be due to the inaccuracy in the measurement of the dose rate from the ^{141}Ce source which had an initial activity of only 25 mCi. The statistics of the calculations give errors of about 4% (standard deviation) with E_c = 50 keV and 6% with E_c = 100 keV.

A typical measured response value for a 0.20-mm detector at 145 keV is shown in the lower part of Fig. 1, based on the comparative calculated and measured values for the 0.27-mm detector using the average of the two values with scattering materials.

The fourth factor affecting the detector response, electron scattering, depends on the materials immediately adjacent to the detector's sensitive volume, and involves transport of the ionizing electrons between the exterior media and the detector. With adjacent materials having a higher photon cross section than the silicon, there will be a net transport of the ionzing electrons into the detector and a resulting increase in response. The response at energies near E_{cc} in Fig. 1 can thus be increased by adding layers of high-atomic-number materials which have relatively large photo-electric cross sections at these energies.

The extent of this increase in response was measured at 145 keV using the arrangement in Fig. 2 with enhancement layers of copper or tin replacing the layers of aluminum normally used. Actually, the enhancement from the front (source side) and the back were checked separately using that surface of the detector (the front gold-plated surface) which was closer to the outer surface to the detector mount. The pulse-height spectra obtained by combining the front and back enhancement measurements are shown in Fig. 4

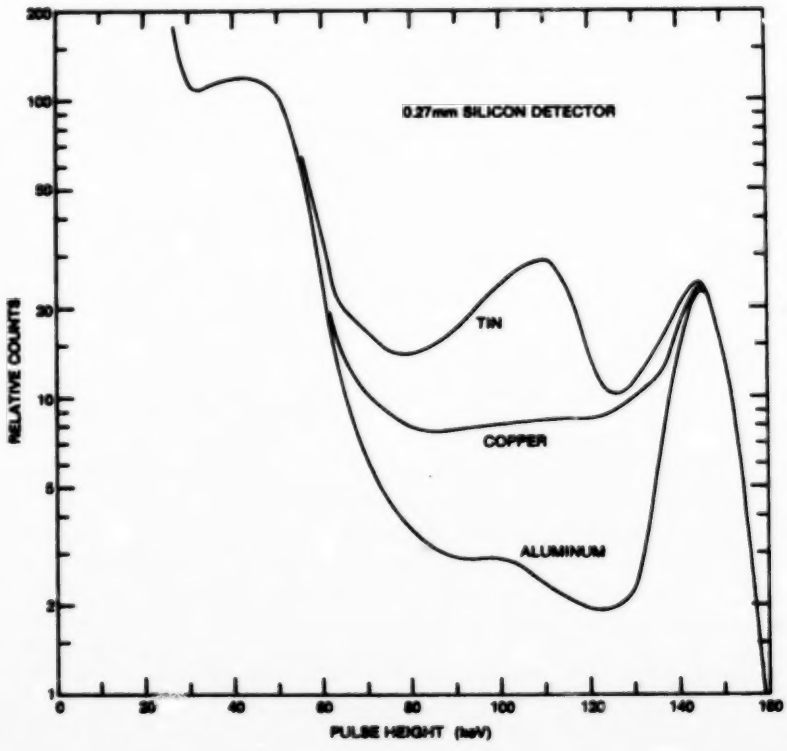

Figure 4. Measured pulse-height spectra obtained using the setup in Figure 2. The tin enhancemnt layers were 0.007 mm in thickness and those of copper were 0.024 mm. This detector had a resolution of 11 keV (FWHM). These spectra contained typically 10,000 counts above 100 keV.

for copper (0.024 mm) and tin (0.007 mm). The maximum at 115 keV with the tin layers results from photoelectric absorption in tin with escape of the tin x-ray of 26 keV. Some of these x-rays are absorbed in the detector in coincidence with the photoelectrons thereby increasing the pulse height for these events so that additional pulses near the photopeak energy are produced.

The computer calculations were extended to include these tin and copper enhancement layers in addition to the calculations at 145 keV which were done with silicon adjacent to the detector. General agreement is seen between the calculated spectra of Fig. 5 and the measured spectra of Fig. 4.

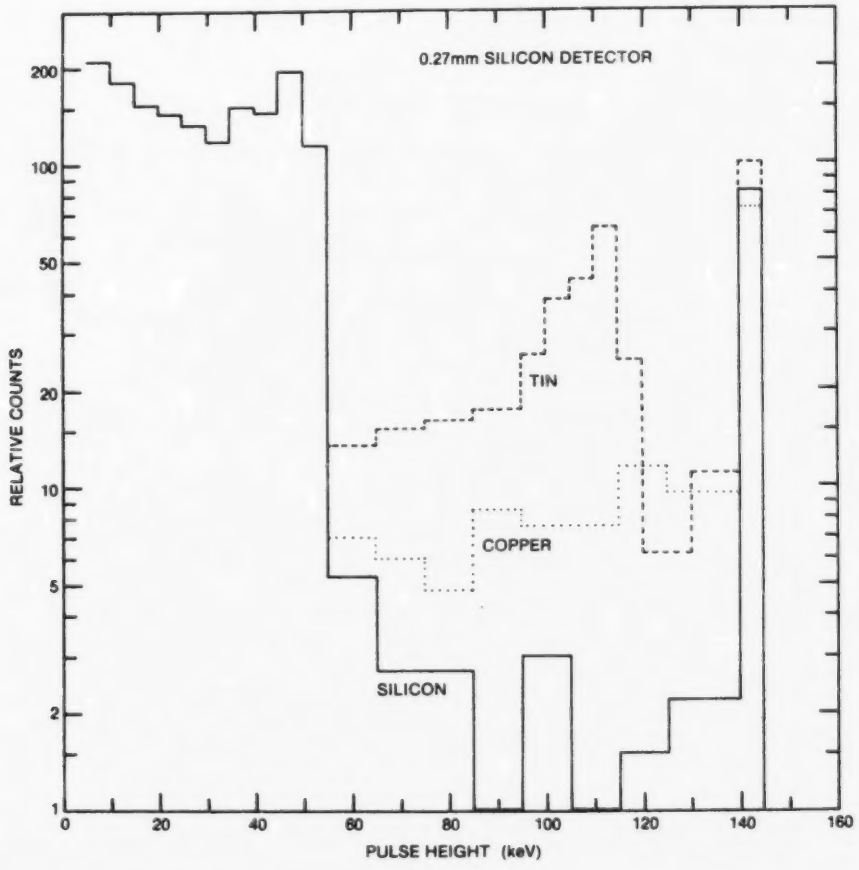

Figure 5. Calculated pulse-height spectra obtained using a detector model simulating the experimental geometry. This detector is noise free. The actual counts generated in the 5-keV bins are three times the ordinate numbers for silicon and twice these numbers for copper and tin.

The calculated spectrum using silicon adjacent to the detector can be considered equivalent to the measured spectrum with the aluminum walls. Below the Compton edge at 53 keV the three spectra are essentially the same and only the unenhanced spectrum is shown. The measured spectra are terminated just below 30 keV since the relative number of counts due to noise from this detector increased sharply with further reduction in energy.

Since the largest uncertainty in the measured response values is the determination of the dose rate from the ^{141}Ce source, the experimental and calculated enhancement can best be compared by using the ratio of the response with and without the tin or copper layers. Enhancement ratios defined as the response of the detector with the tin or copper to that without these layers, are listed in Table II. The actual response values with tin or copper are thus given by multiplying these ratios by the measured (with no scatter) or calculated values in Table I.

TABLE II

Response-Enhancement Ratios of 0.27-mm Silicon Detector at 145 keV Obtained by Sandwiching the Dectector Between Layers of Tin or Copper

E_c (keV)	Tin (.007 mm)		Copper (.024 mm)	
	Measured	Calculated	Measured	Calculated
40	1.51	1.65	1.19	1.16
50	2.00	2.49	1.37	1.35
60	2.72	3.80	1.67	1.75
75	2.89	3.79	1.75	1.74
100	2.40	3.25	1.60	1.57
125	1.27	1.49	1.23	1.20

The measured enhancement ratios for the tin are seen to fall below the calculated values, but the measured response is still measured by almost a factor of three for E_c = 60 keV by the addition of the tin. This thickness of tin is less than the range of a 40-keV electron so that increasing the thickness of the tin can lead to much larger enhancements. The measured and calculated enhancement ratios are in reasonable agreement although the measured values are seen to be somewhat less than predicted. This may be due to small differences in conditions of geometry such as collimation, thickness of tin and separation of the tin and silicon by small distances ($\sim$ 1 mm) and by the detector window. The enhancement of the copper layer is seen to be much less than for the same thickness of tin. The 0.024 mm of copper is about equal to the range of a 100-keV electron, so that increasing the response by further increasing the thickness of this layer is soon limited by electron absorption. Thickness of the copper used is thus less critical than for the tin. Also, material between the detector and the enhancement layers is less effective because of the higher photoelection energy (lower x-ray energy) than for the tin. Excellent agreement is seen between the measured and calculated response-enhancement ratios of the copper.

MODIFICATION OF ENERGY RESPONSE BY THE ADDITION OF THIN LAYERS OF TIN OR COPPER ADJACENT TO DETECTOR

The above methods were used to calculate the response enhancement resulting from the addition of thin layers of tin adjacent to a 0.2-mm thick silicon detector at energies ranging from 0.06 to 0.4 MeV. By varying the thickness of the tin it was estimated that between 0.005 and 0.01 mm of tin are required to adequately increase the response at energies where the minimum is observed with cut-off energies 50 to 75 keV. For gamma energies below about 120 keV, where response enhancement is not required, the tin next to the detector tends to produce a response which is too high. This can be reduced by placing a dead layer between the tin and the detector. For simplicity of calculations, silicon was chosen as a dead-layer material. Aluminum would be essentially equivalent. A thickness of 0.005 to 0.01 mm is sufficient to attenuate a large fraction of the low-energy photoelectrons.

For these calculations, the spectra obtained are similar to those shown in Fig. 5 with the pulse heights of the contributions from the enhancement layers being reduced by attenuation of the photoelectrons in the dead layer between the detector and the tin or copper.

Calculated responses for the 0.2-mm detector are summarized in Table III. Most of the values with no enhancement layer and with the copper layer are taken from Ref. (3) and are repeated here for comparison. These differ slightly from the tabulated values in Ref. (3) which were adjusted to apply for a detector surrounded by 5 mm of silicon. The thickest surrounding layer required for the energies in Table III is 0.3 mm which is sufficient for electron equilibrium at 0.4 MeV

The effect of the enhancement layers is demonstrated in Fig. 6, where the response versus photon energy is plotted for E_c = 60 and 150 keV, with no enhancement layers and with the copper and tin layers used for Table III. Filtration equivalent to 4 g/cm^2 (0.55 mm) of tin has been applied to the incident photons to reduce the resposne at low energies. A dead layer is assumed, between the filter and the enhancement layer, which is thick enough to prevent photoelectrons originating in the filter from reaching the detector.

With E_c = 60 keV the effect of both the copper and tin layers is seen to be large, particularly at energies near 150 keV. The response has been smoothed out considerably in the region of E_{cc} (157 keV), but the average response below 400 keV remains relatively large. The enhancement with E_c = 150 keV is small except for energies between 150 and 300 keV where the photoelectric cross sections contribute relatively large numbers of counts.

While the minimum at E_{cc} has been smoothed out, the over all response is not improved by addition of the enhancement layers. However, having smoothed out the response at the lower photon energies, a better response can now be obtained by increasing the relative response at higher energies by giving more weight to the larger pulses. In the counting mode, a simple method for doing this is by the use of more than one discriminator level as described in Ref.(3). More weight is given to the larger pulses by dividing down the number of counts in a lower-energy group before adding to the number of

TABLE III

Calculated Response of 0.2-mm Silicon Detector Sandwiched Between Layers of Silicon, Copper or Tin as a Function of Photon Energy E_γ and Cut-Off Energy E_c. The Copper Layers Are 0.02 mm in Thickness and Are next to the Detector Surfaces. The Tin Layers Are 0.007 mm in Thickness and Are Separated from the Detector by 0.007 mm of Silicon. Minimum Responses Are Expected at the Effective Compton Cut-Off Energies E_{cc}. Energies Are in keV and the Units of Response Are 10^7 counts/(mm^2 gray).

	E_c = 40 E_{cc} = 123			E_c = 50 E_{cc} = 141			E_c = 60 E_{cc} = 157		
E_γ	Si	Cu	Sn	Si	Cu	Sn	Si	Cu	Sn
60	20.5	21.9	23.0	20.2	18.8	21.2			
70	12.9	16.9	13.9	12.6	15.0	12.8	12.5	12.5	11.6
80	7.6	11.7	9.8	7.5	10.7	8.6	7.3	9.5	7.7
100	3.38	5.2	9.6	3.31	4.7	7.1	3.22	4.4	5.4
125	1.75	3.35	6.74	1.16	2.71	4.96	1.08	2.50	4.44
150	3.47	4.82	6.45	1.90	3.11	4.63	0.56	1.76	3.15
175	3.35	4.11	5.38	2.76	3.23	4.47	1.75	2.27	3.31
200	3.28	3.92	4.32	2.65	3.28	3.64	2.11	2.70	3.07
250	3.02		3.38	2.65		3.01	2.26		2.62
300	2.65		2.94	2.38		2.70	2.12		2.44
400	2.20		2.14	2.04		2.00	1.88		1.87

	E_c = 75 E_{cc} = 181			E_c = 100 E_{cc} = 217			E_c = 125 E_{cc} = 252		
E_γ	Si	Cu	Sn	Si	Cu	Sn	Si	Cu	Sn
80	6.8	7.6	6.3						
100	3.0	3.4	4.0						
125	1.02	2.20	3.30	0.90	1.66	1.69			
150	0.52	1.50	2.83	0.47	1.35	1.89	0.42	0.76	0.75
175	0.31	0.97	1.84	0.27	0.82	1.43	0.24	0.70	1.06
200	1.17	1.76	2.15	0.14	0.60	0.99	0.12	0.49	0.79
250	1.75		2.19	1.01		1.36	0.10		0.44
300	1.76		2.09	1.28		1.56	0.80		1.01
400	1.67		1.68	1.30		1.37	1.00		1.12

	E_c = 150 E_{cc} = 285			E_c = 200 E_{cc} = 347			E_c = 300 E_{cc} = 465		
E_γ	Si	Cu	Sn	Si	Cu	Sn	Si	Cu	Sn
175	0.23	0.39	0.36						
200	0.10	0.39	0.61						
250	0.07		0.40	0.05		0.29			
300	0.31		0.47	0.02		0.22			
400	0.73		0.83	0.34		0.34	0.005		0.0015

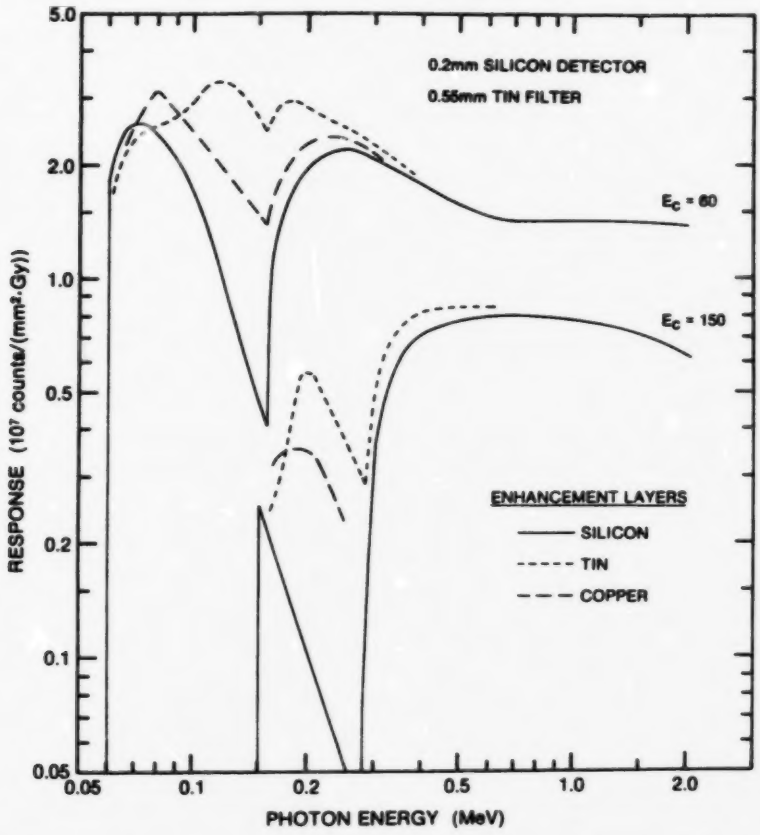

Figure 6. Calculated responses of 0.2-mm silicon detector for cut-off energies of 60 and 150 keV. Comparison of the dashed curves with the solid curves shows the effect of adding the copper (0.02 mm) and tin (0.007 mm) enhancement layers. Layers of silicon (0.007 mm) separated the detector and the tin. Electron-equilibrium layers of silicon were assumed outside the enhancement layers. The tin filter was not included in the computer calculations, filtration being applied according to the photon attenuation coefficients for tin.

higher-energy pulses. For example, the energy response is altered by adding one half of the counts between 60 and 200 keV with all of the counts above 200 keV.

Fig. 7 shows the energy response resulting from some different combinations of discriminator levels, enhancement layers and photon filtration for a 0.2-mm detector. It can be seen that fairly uniform energy response can be obtained with this detector thickness using a variety of the above combinations. Undoubtedly, compensation can be similarly achieved with other detector thicknesses. However, increasing the thickness to 0.5 mm gives only a 50% response increase at ^{60}Co energy, so that there is no great advantage in using a detector thicker than 0.2 mm. On the other hand, decreasing the thickness to 0.1 mm results in a reduction in response by about a factor of two at ^{60}Co energy.

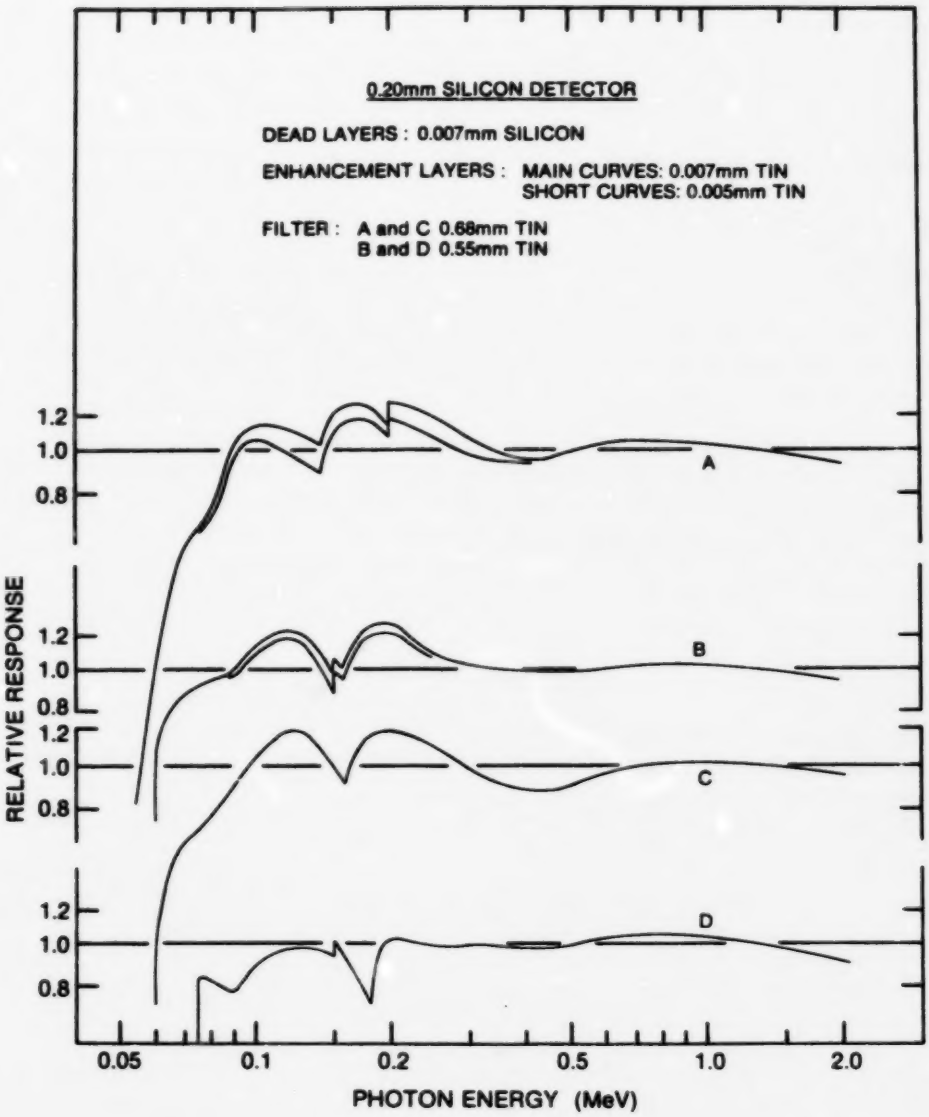

Figure 7. Relative response calculated for several combinations of enhancement layers, filtration and cut-off energies which result in reasonably uniform response between 80 keV and 2 MeV. The cut-off energy groups (in MeV) and weighting factors are: A = (> 0.20) + (0.05 to 0.20) ÷ 2 (all the counts above 0.2 Mev are added to one half of the counts between 0.05 and 0.2 MeV); B = (> 0.30) + (0.15 to 0.30) ÷ 2 + (0.06 to 0.15) ÷ 4; C = (> 0.30) + (0.20 to 0.30) ÷ 2 + (0.06 to 0.20) ÷ 4; D = (> 0.30) + (0.15 to 0.30) ÷ 2 + (0.075 to 0.15) ÷ 4. Using the thinner enhancement layers for A and B, all four combinations of energy groups give responses which with very minor exceptions are seen to be within 20% of the values at 1.25 MeV.

SUMMARY AND CONCLUSIONS

Various mechanisms which tend to modify the response of silicon radiation detectors, operating in the pulse-counting mode, have been considered with particular emphasis on the enhancement of the response at the minimum corresponding to the effective Compton cut-off energy. Detector noise, spread in source energy and photon scattering all tend to smooth out the energy respose near this minimum. The effect of photon scattering has been investigated briefly using a ^{141}Ce source of energy 145-keV.

Calculations have been carried out to determine the modification of the energy response of a 0.2-mm silicon detector by the addition of thin layers of tin or copper. The results using tin have been combined with previous response calculations to give predictions of response which are flat to within ± 20% over the energy range of 80 keV to 2 MeV, providing that appropriate combinations of photon filtration, cut-off energies and thickness of tin are chosen.

The practicability of using metal foils to enhance the response to the ^{141}Ce source was demonstrated using tin and copper next to the surfaces of a silicon particle detector. The measured enhancements were in good agreement with increases in response predicted by the computer program.

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13 ABSTRACT

The response enhancement of a silicon radiation detector by the addition of thin layers of copper or tin has been investigated experimentally at 145 keV and by computer methods over a range of photon energies. It has been demonstrated that this technique can be used, along with the appropriate choices of photon filtration and cut-off energies, to improve the energy response of a silicon detector of thickness 200 to 300 μm.

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KEY WORDS

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Silicon Detector
Energy Response

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